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Experimental Results from a 6kW High-temperature Steam Electrolysis Unit Connected to a Lab-scale BOP with Helium Heating Loop

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1. Introduction

Hydrogen production efficiency using High Temperature Steam Electrolysis (HTSE) improves as the temperature of the supplied steam increases. A lab-scale balance of plant (BOP) to generate high-temperature steam is designed and constructed for 30kW HTSE using solid-oxide electrolyte cell stacks at the Korea Atomic Energy Research Institute (KAERI) [1]. The BOP is designed and manufactured to heat the steam and air up to 800℃ with the heated helium (Fig. 1). Plate-type SOEC stack for HTSE has the advantage of being highly manufacturable and having a dense structure with very high hydrogen production efficiency. However, it is very sensitive to thermal shocks and rapid heating or cooling should be avoided during stack operation [2]. We prepared the units of 30 kW SOEC testable capacity, and a 6 kW SOEC test is carried out to validate the performance with the lab-scale BOP.

2. Lab-scale BOP for 30kW HTSE

An experimental facility is designed and constructed at KAERI for 30kW HTSE test using solid-oxide electrolyte cell (SOEC) stacks. Fig. 2 describes a schematic of the experiment facility for 30kW HTSE system with helium loop as a heat source. The facility is composed of the major components such as a helium loop (lab-scale loop electrically simulating a VHTR), air and purified water supply system, HTSE including SOEC, steam generator, multi-stream heat exchanger (MHX), gas supply system and two auxiliary heating units(Unit-A for the steam line, Unit-B for the airline).

The experiment facility equipped a 77 kW heating system to heat the helium up to 1000℃, and a shell and helical-tube type steam generator and a MHX are manufactured to heat both the steam and air up to 800℃ with the heated helium. Purified water is evaporated via the steam generator and the steam is superheated through the MHX. Air is heated up through the MHX also, and it is used as sweep gas of anode side in SOEC stacks.

3. Plate-type SOEC stack for HTSE

Fig. 3 shows a schematic diagram of the HTSE connected to the heat source. In the cathode, high temperature steam is reduced and decomposed into hydrogen and oxygen ions. The oxygen ion from cathode is transferred to the anode, and the oxygen is produced in the anode by oxidizing oxygen ion. The generated hydrogen flows out of the stack along with the remaining steam and then passes through a condenser to remove the remaining steam.

SOEC stacks that require an operating temperature of 600~900℃ are usually installed inside a high-temperature environment hotbox to execute electrolysis operation. The SOEC has a steam channel to separate hydrogen and an air channel to blow out oxygen, a by-product, and the steam and air entering the SOEC must be preheated to the SOEC operating temperature for high-temperature operation. The steam supplied by the SOEC requires a constant, high-purity steam supply. An unstable flow rate of steam can cause pressure waves that can damage the sensitive SOEC stack internals.

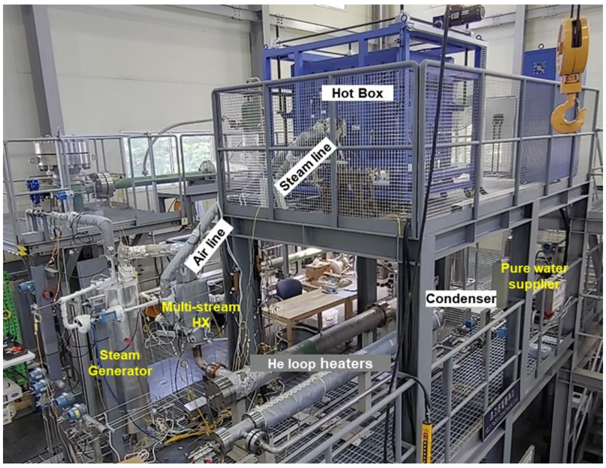


Fig. 1. Picture of the lab-scale BOP for 30kW HTSE

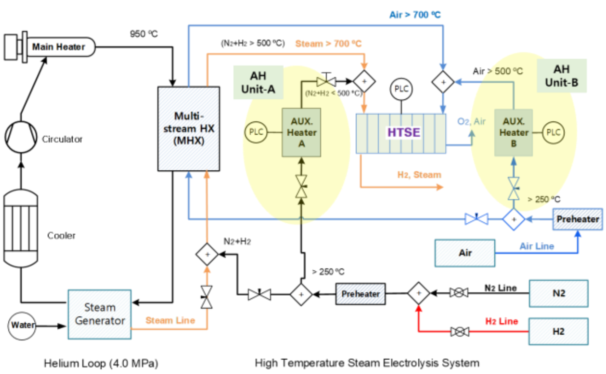


Fig. 2. Layout of the lab-scale BOP

On the other hand, the sealant of the SOEC stack is a glass material that is sensitive to high temperature thermal expansion [2]. The high temperature difference between cells can cause cracks in the glass material, which is the main cause of steam leakage, so controlling the temperature difference during cooling and heating is very important. Therefore, the lab-scale BOP for a HTSE that can meet these various operating requirements are necessary for stable SOEC operation. We summarized these requirements in Table I and quantify an approximate value for each

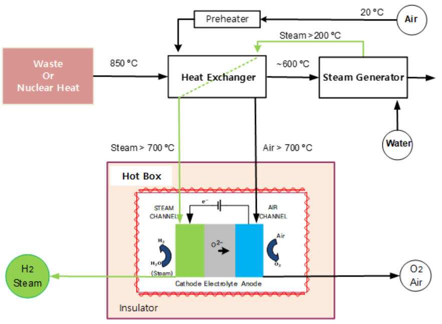


Fig. 3. Schematic diagram of the HTSE connected to the heat source.

Table I. General requirements of the BOP

Requirement	Value	Prevent
Purified water	MΩ level	Oxidation, Contamination
Purified air	Moisture & oil free	Contamination
Stack pressure	< 50 kPa	Leakage, Sealant failure
Stack heating	0.5~1.0°C /min (Plate type)	Leakage, Sealant failure
Hot box temp.	700~1000°C	Heat loss
Hydrogen injection	Max. 25% (Volume ratio)	Oxidation (Cathode)

4. Heat loss compensation system

The 700°C air and steam required to operate the SOEC is heated through a MHX, which is supplied with helium gas heated to over 900°C as shown in Fig. 2. However, heat losses occur in the hot piping between the MHX and the SOEC installed inside the hotbox, causing the inlet gas temperature to drop. Therefore, it is necessary to compensate for the temperature drop. Heat loss compensation can be achieved by wrapping a flexible wire heater around the outside of the tube to compensate for heat loss. Fig. 4 shows a map of heat loss compensation zones for the 6 kW HTSE test rig. Each of the eight zones utilizes a PLC(Programable Logic Controller) for precise temperature control of the inlet gases as the SOEC temperature rises.

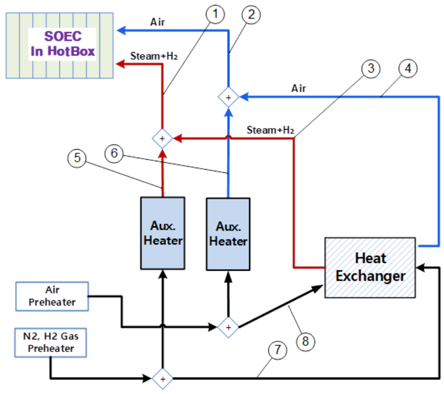


Fig. 4. Map of heat loss compensation zones

5. Experiments

5-1 SOEC test rig

The 6kW test rig consisted of two 3 kW SOECs connected in parallel (Fig. 5). The connecting piping is insulated with a heating jacket at the hotbox inlet and uninsulated at the hotbox outlet.

Normal operating conditions are as follows;

- Hotbox temperature: 730°C
- Steam flowrate: 3.5 kg/hr
- Air flowrate: 80.0 SLPM

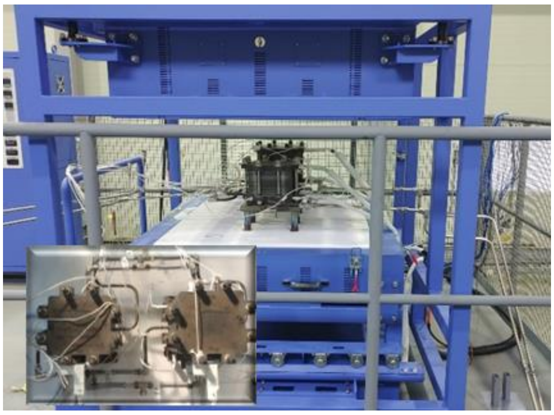


Fig. 5. Test rig for 6kW SOEC in hotbox

5-2 Test procedure

Fig. 6 shows operating procedure for a 6.0 kW capacity HTSE system. A start-up operation phase that gradually heats up at a rate of 1.0°C/min, a stack temperature stabilization phase, a hydrogen production test phase, and a shutdown phase that gradually reduces the temperature. The flow rate of various gases such as steam, air, and hydrogen supplied to the 6kW SOEC is determined for each stage of operation. Little amount of hydrogen (safe gas) is injected into the steam channel as a reducing agent. This is to address the issue that steam can oxidize SOEC electrode materials at high temperatures. SOEC utilizes nitrogen instead of steam for both the heating and cooling stage.

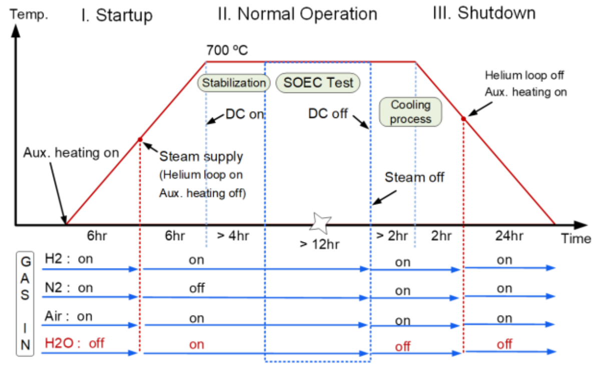


Fig. 6. Procedure of stack operating with lab-scale BOP

6. Results and Discussion

In terms of first checking the performance of the BOP, including the helium system connected to the HTSE system, the following questions arose prior to the test,

- Can the BOP provide a steady supply of steam/air above 700°C at the inlet to the stack for a long period of time?
- Is hydrogen production good?
- Is the pressure drop in the stack small enough?
- Is the pressure drop at the condenser as small as predicted?
- Does the heating jacket maintain its performance?
- Is the auxiliary heating system useful?

There are many questions about the operation of the stack in conjunction with the BOP, but this experiment answered most of them. The stability of the helium loop and the steam/air production system, which are the core systems of the BOP, was already demonstrated experimentally by Hong et al. in 2023 [1], but is confirmed once again in the stack-connected state. The stack inlet temperature of 700°C is achieved by self-heating in the hotbox.

As shown in the graph of the test results in Fig. 7, the steam/air temperature up to the hotbox inlet was just over 550°C, while it reached 700°C at the stack inlet. A quantitative analysis of the self-heating in the hotbox was performed by Hong et al. in 2024 [3]. Self-heating is more effective when the set temperature of the hotbox is kept higher than 700°C. In this experiment, the temperature of the hotbox is kept at 730°C for steady-state experimental conditions. The temperature raised by self-heating is predicted by the analytical method to be somewhat lower than the experimental value (Fig. 8). To compensate for heat loss, a high-temperature wire heater can maintain performance up to a piping surface temperature of 700°C, but a surface temperature of 600°C is appropriate for long-term use of the wire heaters. We can assume that the gas enters the hotbox at 600°C and calculate the length of connecting pipe required to achieve a 700°C gas mixture temperature by self-heating inside the furnace as shown in Fig. 8.

When DC power is applied to the stack 15 hours after the start of the experiment, a sharp drop in pressure and temperature occurred (Fig. 9). This is presumed to be due to the initiation of the endothermic reaction of hydrogen decomposition from the steam in the stack in response to the power supply, resulting in a rapid decrease in the temperature of the gas, followed by a rapid decrease in the density of the gas due to the rapid decrease in temperature, resulting in a rapid decrease in pressure. The hydrogen and residual steam generated after the steam electrolysis reaction pass through a pool-type condenser, where the steam is condensed and trapped, and the hydrogen is discharged to the atmosphere after passing through the condenser.

7. Conclusions

A lab-scale balance of plant (BOP) to generate high-temperature steam is designed and constructed for 30kW HTSE using solid-oxide electrolyte cell stacks. The stability of the helium loop and the steam/air production system, which are the core systems of the BOP, is confirmed in the 6.0kW SOEC stack-connected state.

Lessons learned after testing the lab-scale BOP connected to a 6kW HTSE system:

- the excessive heat loss occurred at the connecting pipes (insulation limit).
- Gas heating in the hotbox is very useful for stacks and the BOP operation.

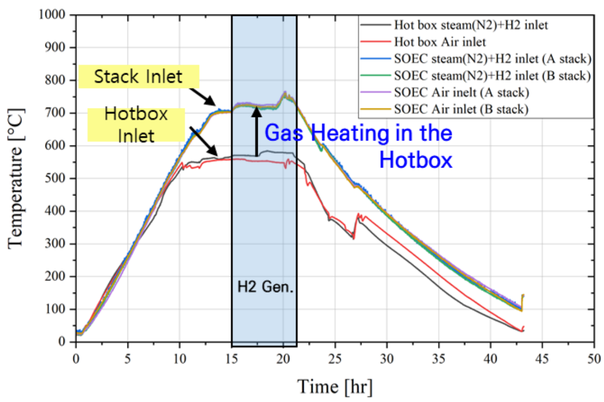


Fig. 7. Measured gas temperatures in the hotbox

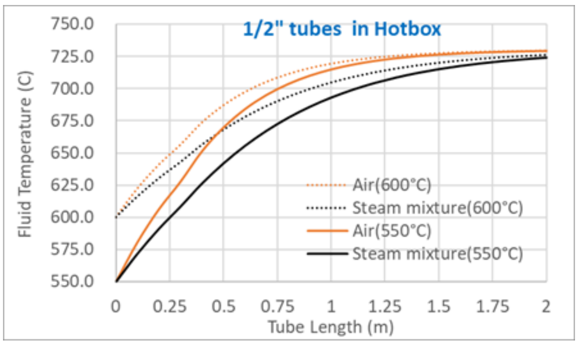
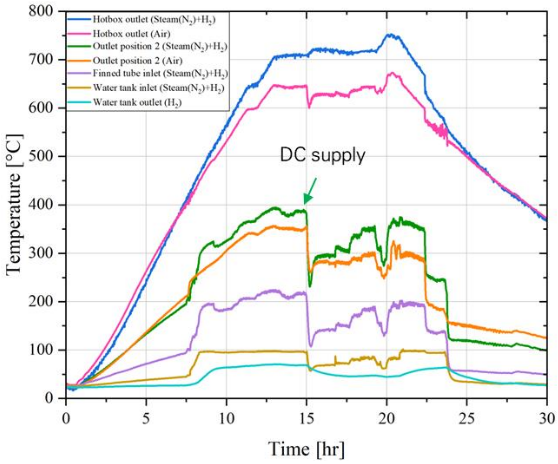
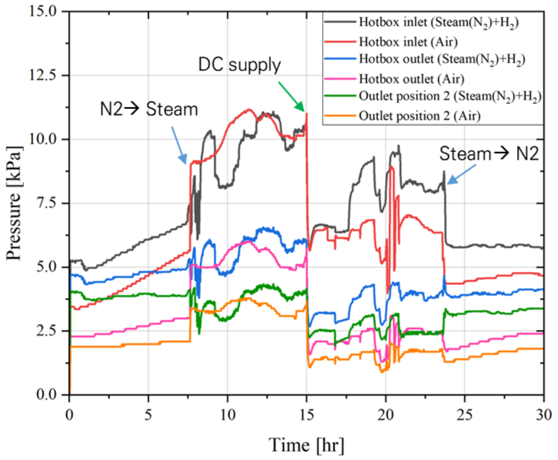


Fig. 8. Gas temperature recovery in 730°C hotbox, Channel(tube) length in hotbox: Air side = 0.5m, Steam side = 0.7m (Steam mixture: steam 0.9g/s, H_2 0.025g/s)



(a) Gas temperature



(b) Channel pressure

Fig. 9. Trends in measured gas temperature and gas pressure

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